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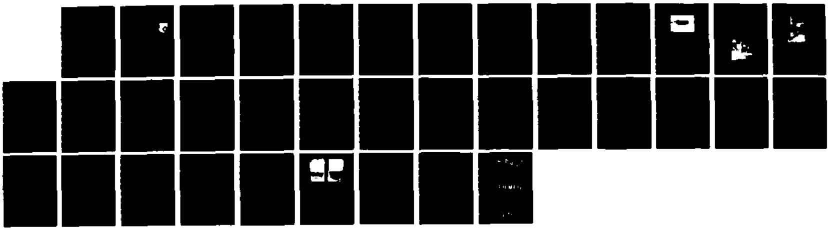

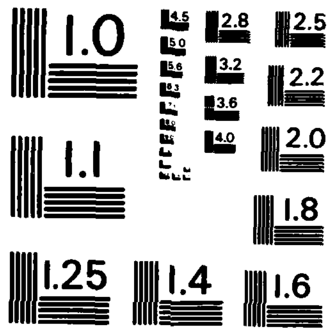
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THERMAL MECHANICAL FATIGUE CRACK GROWTH

AN APPLICATION FOR FRACTURE MECHANICS ANALYSES OF GAS TURBINE ENGINE DISKS

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March 1985

Interim Report for Period March 1981 - June 1983

Approved for public release; distribution unlimited.

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NOTICE

This technical report has been reviewed and is approved for publication.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The capability of the existing Hyperbolic Sine Model to accurately or conservatively predict the crack growth in engine components subject to thermal mechanical fatigue (TMF) was investigated.

It was determined that existing empirical crack growth models adequately predict TMF crack growth under conditions tested, which reflect the current gas turbine engine Retirement for Cause requirements/applications.

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FOREWORD

This interim report documents work as a task entitled "Thermal Mechanical Fracture Mechanics (No. 133)" under the Air Force Wright Aeronautical Laboratories Engine Component Retirement for Cause, Contract No. F33615-80-C-5160 with the Project Number assigned as DARPA 3993. This is an ongoing contract effort. This report is published in compliance with the Contract Data Requirements List and describes the technical accomplishments of the Thermal Mechanical Fracture Mechanics Task.

The Air Force RFC Program Manager is Dr. W. H. Reimann, and the Project Engineer is 1st Lt. R. Sincavage, both of the Air Force Wright Aeronautical Laboratories, Metals Behavior Branch of the Materials Laboratory (AFWAL/MLLN). The program is conducted by the Materials Engineering and Technology Laboratories of Pratt & Whitney, Engineering Division – South (P&W/ED — S), West Palm Beach, Florida. The Project Engineer is R. White and the Program Manager is J. A. Harris, Jr., reporting through M. C. VanWanderham, Manager, Mechanics of Materials and Structures.

The Engine Component Retirement for Cause program is jointly sponsored by the Materials Sciences Office, Defense Advanced Research Projects Agency (DARPA), and the Materials Laboratory, Air Force Wright Aeronautical Laboratories. DARPA and the U.S. Air Force participant contributions to the program and to the work reported herein are acknowledged and appreciated.

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INTRODUCTION

RETIREMENT FOR CAUSE BACKGROUND

Historically, methods used for predicting the life of gas turbine engine rotor components have resulted in a conservative estimate of useful life. Most rotor components are limited by low-cycle fatigue (LCF) generally expressed in terms of mission equivalency cycles or engine operational hours. When some predetermined life limit is reached, components are retired from service.

Total fatigue life of a component consists of a crack initiation phase and a crack propagation phase. Engine rotor component initiation life limits are analytically determined using lower bound LCF characteristics. This is established by a statistical analysis of data indicating the cyclic life at which 1 in 1000 components, such as disks, will have a fatigue induced crack of approximately 0.030 inch surface length. By definition then, 99.9% of the disks are being retired prematurely. It has been documented that many of the 999 remaining retired disks have considerable useful residual life. Under the Retirement for Cause (RFC) philosophy, each of these disks could be inspected and returned to service. The return-to-service (RTS) interval is determined by a fracture mechanics calculation of remaining propagation life from a crack just small enough to have been missed during inspection. This procedure could be repeated until the disk has incurred measurable damage, at which time it is retired for that reason (cause). RFC is a methodology under which an engine component would be retired from service when it had incurred quantifiable damage, rather than because an analytically determined minimum design life had been reached.

The Materials and Aeropropulsion units of the Air Force Wright Aeronautical Laboratories (AFWAL) have been conducting in-house research and development activities in the RFC area since 1972. A joint study of the Metals Behavior Branch (AFWAL/MLLN), the Engine Assessment Branch (AFWAL/POTA), and the Directorate of Engineering, Aeronautical Systems Division (Reference 1) was undertaken in 1975 to assess the state of the art of the technologies involved in RFC. This study addressed and used a TF33 3rd-stage turbine disk as a demonstration vehicle. As a result of this study, the technical requirements for implementing an RFC approach were identified. These technology requirements fell into four areas: stress analysis, crack growth analysis, nondestructive evaluation (NDE), and mechanical testing. P&W had also begun extensive research and development programs under corporate, IR&D, and Government contract sponsorship in 1972 to identify and develop the applied fracture mechanics and NDE technologies necessary to realize the RFC concept. In addition to the technical areas defined by the efforts discussed above, the broad areas of economics and logistics management must also be incorporated and integrated before RFC could become a viable, implementable maintenance concept for managing life limited gas turbine engine components.

The culmination of these preliminary activities was a study conducted by P&W/ED — S from 1979 to 1980 under DARPA and AFWAL sponsorship entitled "Concept Definition: Retirement for Cause of F100 Rotor Components" (Reference 2). This program was the first to consolidate and focus these disciplines on a specific engine system and to quantify the benefits and risks involved. Upon completion of the initial Concept Definition Study, the AFWAL/Materials Laboratory established a major thrust in RFC with the goal of reducing the concept to practice with first system implementation to occur in early 1986 on the F100 engine at the San Antonio Air Logistics Center (SA-ALC). P&W/ED — S is developing the probabilistic life analyses and integrated logistics/economic methodology to support this implementation.

THERMAL MECHANICAL CRACK GROWTH

The two studies previously referenced both cited the importance of accurate crack growth analyses in enabling the RFC concept to be implemented with confidence. As a part of the ensuing "Engine Component Retirement For Cause" contract program, several areas of concern in conducting crack growth analyses of gas turbine engine disks were identified. Included in those concerns was the impact that the temperature-load range conditions which exist near the rim of a turbine disk may have upon the adequacy of the crack growth predictions for potential flaws in that area of a disk. Traditionally, these crack growth predictions are made using isothermal crack growth data at the temperature corresponding to the maximum loads expected to exist. In general, the predictions are accurate, or at least conservative. The purpose of the effort reported here was to conduct a limited experimental program to assess the adequacy of using isothermal (temperature constant, load cycling) as opposed to thermal mechanical fatigue (TMF) (with both temperature and load cycling) crack growth data for predictions of gas turbine disk life. This effort was not intended to be an exhaustive investigation of thermal mechanical fracture mechanics, but focused upon materials and conditions typical of disks in an advanced tactical fighter engine such as the F100. Other extensive AFWAL programs are addressing thermal mechanical fatigue for turbine airfoil (blade) materials and conditions (References 3, 4).

The specific objectives were to: (1) evaluate any differences in crack growth rate in the nickel-base turbine disk materials Astroloy and IN100 between isothermal and thermal mechanical cycling and (2) assess the impact these differences, if any, might have upon the implementation of the RFC concept for these materials. Using the existing interpolative Hyperbolic Sine Model (SINH) the method of evaluation was to compare crack growth rate (da/dN versus ΔK) data generated under isothermal conditions with data for the same materials tested under thermal mechanical conditions. The crack growth data was obtained from test specimens subjected to in-phase and out-of-phase thermal mechanical cycling. An in-phase cycle has its maximum tensile load at the maximum temperature of the cycle; an out-of-phase cycle has the maximum tensile load at the minimum temperature of the cycle. Isothermal crack growth data was obtained from the existing data base for these materials at constant temperatures corresponding to the maximum and minimum temperatures of the thermal mechanical cycle.

The experimental program, results and conclusions of this effort, are discussed in the following paragraphs.

SECTION II

EXPERIMENTAL PROGRAM

As shown in Figure 1, the experimental testing conducted in support of this program is summarized in Table 1. ASTM standard center-crack-tension (CCT) specimens, fabricated from Astroloy and IN100 were used.

TEST METHOD

The TMF test system used in this task (Figure 2) is a conventional servo-hydraulic test machine which has been modified to simultaneously ramp and control temperature and stress. The machine contains two electronically controlled servo-systems: one is a hydraulic system for closed-loop control of load, strain or displacement; the other is used concurrently for closed-loop control of specimen temperature. Command waveforms for each parameter are independent and can be programmed to conduct any TMF test cycle within the ramp rate capacity of the servo-systems.

Temperature control is accomplished using direct resistance heating from a low voltage-high current transformer and external air cooling. The transformer primary is driven by a variable voltage, phase angle fired power control circuit. Current from the transformer is passed through the insulated load fixturing to the specimen and back to the transformer. The high current (0 to 1200 amperes at 0 to 3 volts AC) passing through the minimum cross section of the specimen supplies the thermal energy for rapid heating. Controlled closed-loop heating rates of 56°C (100°F) per second or less are generally used for TMF testing. However, open-loop rates of 556°C (1000°F) per second are available. For the cooldown portion of the waveform, the servo-system applies only the quantity of air required to maintain the temperature ramp. With the addition of water-cooled heat sinks to the specimen fixturing (Figure 3), sufficient cooling (approximately 28°C (50°F) per second maximum) can be obtained by conduction to reduce the through-thickness temperature gradients. The cooling is so efficient that the fixture is only warm to the touch at the maximum specimen temperature. A surface temperature profile around the crack using pyrometry, showed no localized surface crack tip temperature differential. This test method has been successfully used previously for screening and alloy/coating system development (Reference 5). All the precracking and testing was performed generally in accordance with procedures outlined in ASTM E647-83 except for the variation in test temperature. The crack lengths were measured on both sides of the notch and on front and back surfaces directly with a traveling microscope. Typical TMF temperature/load waveforms are shown in Figure 4. TMF testing with an in-phase cycle shape has the maximum load occurring at the maximum temperature. In the out-of-phase cycle, maximum load occurs at the minimum temperature. Two stress ratios ($R = 1.0$ and 0.1) were used for the out-of-phase testing.

Maximum cyclic temperatures were 538°C (1000°F) for IN100, and 510°C (950°F) for Astroloy. Minimum cyclic temperatures were 260°C and 149°C (500°F and 300°F) for IN100, and 260°C and 93°C (500°F and 200°F) for Astroloy. The test frequency was established at 0.5 cycles per minute (cpm) to permit sufficient time for cooling the test specimen thereby minimizing the amount of air cooling required.

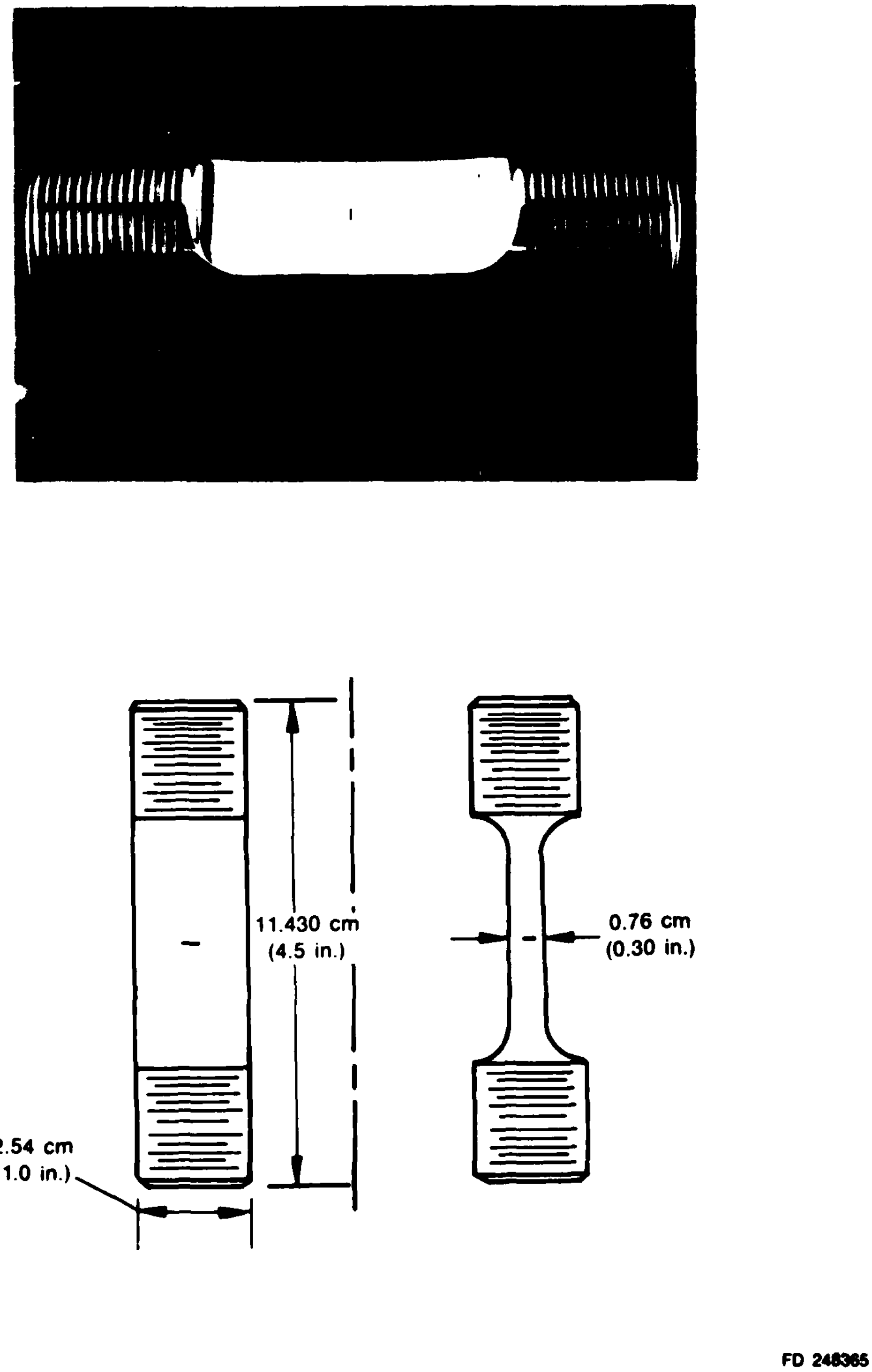

Figure 1. ASTM Standard Center-Crack-Tension Specimen

TABLE 1. THERMAL MECHANICAL FRACTURE MECHANICS TEST MATRIX

Material	*Specimen Number*	*Temperature Range*	*Stress Ratio*	*Cycle Type*
Astroloy				
	2125	200°F to 950°F	−1.0	Out-of-Phase
	2126	200°F to 950°F	0.1	Out-of-Phase
	2127	500°F to 950°F	−1.0	Out-of-Phase
	2128	200°F to 950°F	−1.0	In-Phase
	2129	500°F to 950°F	−1.0	In-Phase
	2130	500°F to 950°F	−1.0	In-Phase
	2131	200°F to 950°F	−1.0	In-Phase
	2132	500°F to 950°F	−1.0	Out-of-Phase
	2133	200°F to 950°F	0.1	Out-of-Phase
	2134	200°F to 950°F	−1.0	Out-of-Phase
IN100				
	2227	500°F to 1000°F	−1.0	In-Phase
	2228	500°F to 1000°F	−1.0	In-Phase
	2229	300°F to 1000°F	−1.0	In-Phase
	2230	300°F to 1000°F	−1.0	In-Phase
	2231	500°F to 1000°F	−1.0	Out-of-Phase
	2232	500°F to 1000°F	−1.0	Out-of-Phase
	2233	300°F to 1000°F	−1.0	Out-of-Phase
	2234	300°F to 1000°F	−1.0	Out-of-Phase
	2235	300°F to 1000°F	0.1	Out-of-Phase
	2236	300°F to 1000°F	0.1	Out-of-Phase

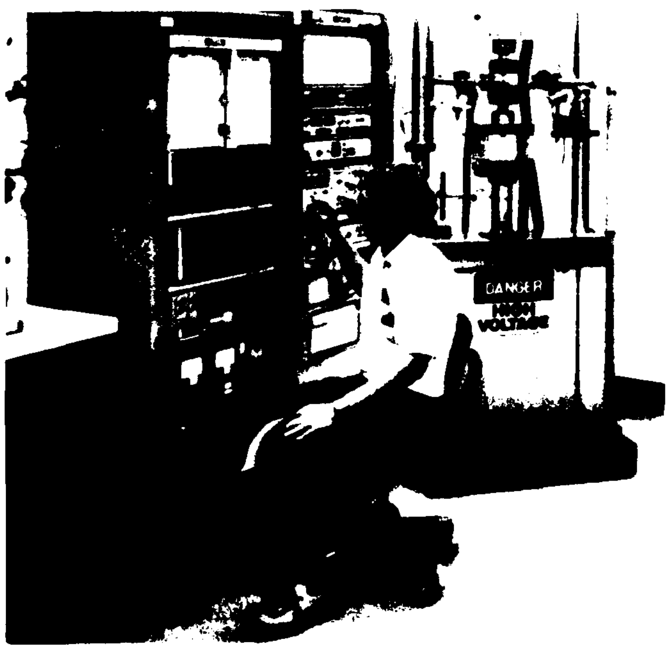

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Figure 2. TMF Test System

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Figure 3. TMF Crack Growth Specimen in Direct Resistance Insulated Load Fixturing

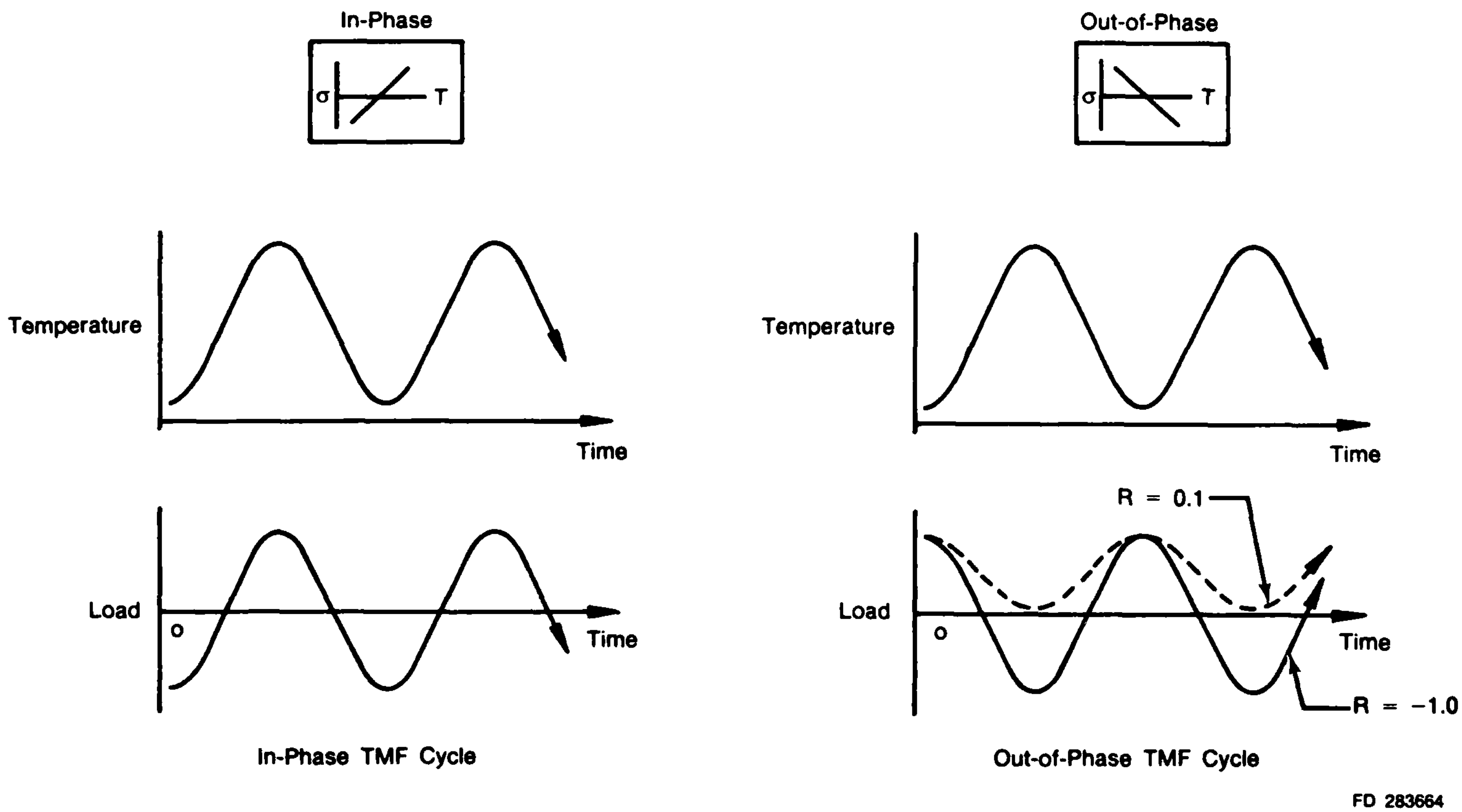

Figure 4. Typical Temperature/Load Waveforms

SECTION III

DATA ANALYSIS TECHNIQUE

The fundamental analytical tool used in assessing TMF crack growth is the SINH model developed under Air Force Contract F33615-75-C-5097. This computer-based interpolative crack propagation modeling system has demonstrated effectiveness under isothermal conditions and may be readily expanded to include thermal mechanical effects. The existing isothermal models were developed from an extensive data base and describe crack growth over a broad range of temperature and loading conditions for several alloy systems. Based on this established system, development of a thermal mechanical crack growth model required minimal additional testing and analysis.

The interpolative Hyperbolic Sine Model (SINH) is in the form of computer software capable of describing crack propagation at various stress ratios, temperatures, and frequencies representative of gas turbine engine operation. The model is based on the hyperbolic sine equation:

$$\log(da/dN) = C_1 \sinh (C_2 (\log\Delta K + C_3)) + C_4$$

where the coefficients have been shown (References 6, 7, and 8) to be functions of test frequency (ν), stress ratio (R), and temperature (T):

$$C_1 = \text{material constant}$$
$$C_2 = f_2 (\nu, R, T)$$
$$C_3 = f_3 (\nu, R, T)$$
$$C_4 = f_4 (\nu, R, T).$$

Because of the simple relationships observed between the coefficients of the SINH model and the fundamental propagation controlling parameters, interpolations are straightforward. It is here the model demonstrates its great usefulness: the hyperbolic sine model provides descriptions of crack propagation characteristics where data are unavailable.

The procedure known as the interpolation algorithm for calculating the SINH coefficients, describing the fatigue crack propagation under representative engine operating conditions, is illustrated as follows. The coefficient (e.g., C_2, C_3, and C_4), at any intermediate value of an element life controlling parameter, can be determined from:

$$Cj = Cj\ \text{base} + \Delta Cj; \qquad j = 2, 3, 4$$

where

$$Cj = \begin{bmatrix} C_2 \\ C_3 \\ C_4 \end{bmatrix} = \text{interpolated values of coefficients}$$

and

$$\Delta\ Cj = \begin{bmatrix} \Delta\ C_2 \\ \Delta\ C_3 \\ \Delta\ C_4 \end{bmatrix} = \text{differences from baseline values.}$$

Since the SINH coefficients are linear functions of the controlling parameters (strictly speaking, the coefficients are nonlinear functions of v, R, and T; however, they are linear functions of other functions), this simplification was used here for presentation clarity.) It is evident that:

$$\begin{bmatrix} C_2 \\ C_3 \\ C_4 \\ N \times 1 \end{bmatrix} = \begin{bmatrix} \partial C_2/\partial v, & \partial C_2/\partial R, & \partial C_2/\partial T \\ \partial C_3/\partial v, & \partial C_3/\partial R, & \partial C_3/\partial T \\ \partial C_4/\partial v, & \partial C_4/\partial R, & \partial C_4/\partial T \\ & N \times N & \end{bmatrix} \times \begin{bmatrix} \Delta\ v \\ \Delta\ R \\ \Delta\ T \\ N \times 1 \end{bmatrix}$$

where

$$\begin{bmatrix} \Delta\ v \\ \Delta\ R \\ \Delta\ T \end{bmatrix} = \text{difference from baseline values}$$

and the $N \times N$ partial derivative matrix is easily determined from the slopes of the lines relating each coefficient with each rate controlling parameter. The computation of the intermediate coefficients is then straightforward.

The goal of this procedure is to determine model coefficients for which the resulting curve through the data will have the least (minimum) summed squared error between calculated and observed values for the dependent variable (Figure 5). In this instance, the independent and dependent variables, x and y, are log (ΔK) and log (da/dN), respectively.

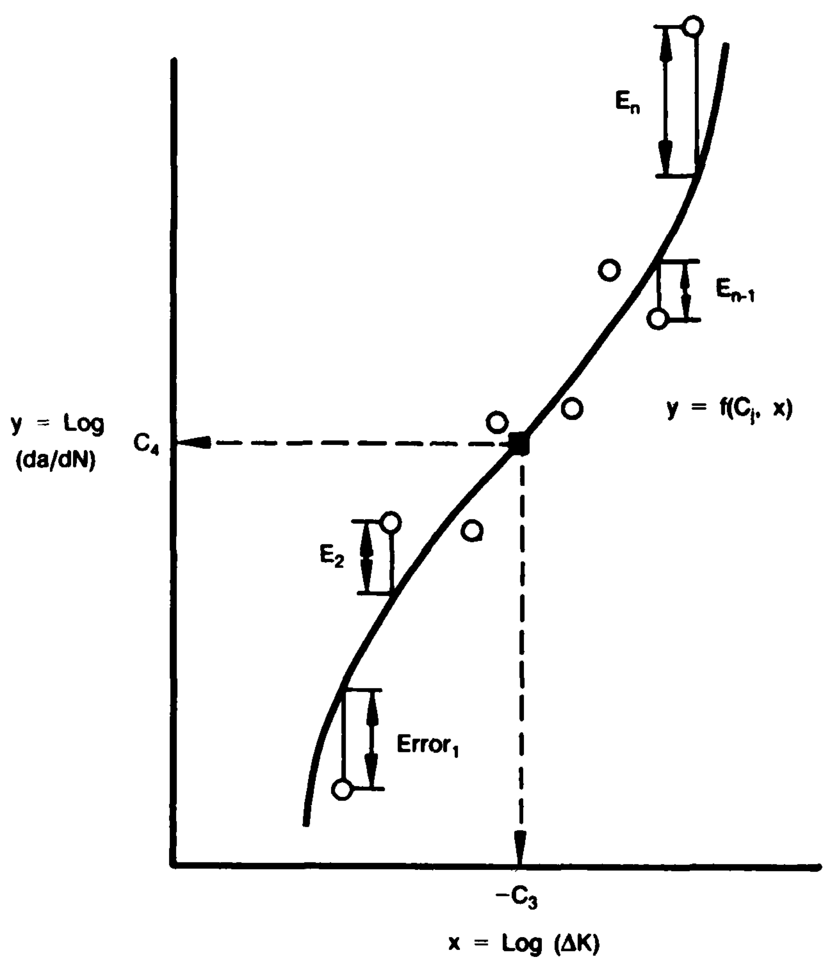

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Figure 5. Model Development Using the Method of Least Squares

Define the sum of the squared errors as

$$E^2 = \sum_{i=1}^{n} E_i^2 = \sum_{i=1}^{n} (y_{cal_i} - y_i)^2 \tag{1}$$

Since $y_{cal_i} = f(C_2, C_3, C_4, x_i)$, E is also a function of C_2, C_3, C_4.

Now, E^2 will be a minimum when each of its partial derivatives is zero simultaneously. That is

$$\frac{\partial E^2}{\partial C_2} = \frac{2E\partial E}{\partial C_2} = 0 \tag{2}$$

$$\frac{\partial E^2}{\partial C_3} = \frac{2E\partial E}{\partial C_3} = 0 \tag{3}$$

$$\frac{\partial E^2}{\partial C_4} = \frac{2E\partial E}{\partial C_4} = 0 \tag{4}$$

when f is the SINH model,

$$E_i = C_1 \text{ SINH } (C_2(x_i + C_3)) + C_4 - y_i \tag{5}$$

and

$$\frac{\partial E}{\partial C_2} = C_1 \text{ cost } (C_2(x_i + C_3))(x_i + C_3) \tag{6}$$

$$\frac{\partial E}{\partial C_3} = C_1 \text{ cost } (C_2(x_i + C_3))(C_2) \tag{7}$$

$$\frac{\partial E}{\partial C_4} = 1 \tag{8}$$

Now, substituting Equations 5, 6, 7, and 8 into Equations 2, 3, and 4, and solving the resulting three simultaneous equations provides the values for C_2, C_3, and C_4 for which Equation 1 will be a minimum.

SECTION IV

RESULTS

No significant difference in crack growth rate was observed for Astroloy or IN100 subjected to an out-of-phase thermal cycle at stress ratios of -1.0 and 0.1 as illustrated in Figures 6 and 7. This indicated that no discernible damage (creep or slip) occurred during the high temperature compressive portion of the cycle.

Comparisons of TMF in phase and out of phase crack growth rate dat[illegible] mparable temperature ranges for Astroloy and IN100 are plotted in Figures 8 th[illegible] or both materials, the in-phase specimen tests exhibit more rapid crack growth t[illegible] f-phase tests. The larger quantity of data scatter observed in Astroloy likely results [illegible] ucture variation found in ring forgings for this material. Since the IN100 data exhib[illegible] tter, the Astroloy data scatter are not attributed to the test equipment or procedures.

No discernible difference was observed between the Astroloy in-phase TMF (with T_{max} 510°C (950°F)) and 510°C (950°F) isothermal data at the same frequency and stress ratio (Figure 12), or for IN100 out-of-phase TMF when compared to 149°C and 260°C (300°F and 500°F), 10 cpm isothermal data (Figures 13 and 14, respectively). A comparison of IN100 TMF in-phase data with 538°C (1000°F), 10 cpm isothermal data (Figure 15) showed the crack growth rate isothermally to be slightly slower than for TMF. This effect is due to the higher frequency of the isothermal data (10 cpm versus 0.5 cpm for TMF tests; no isothermal 0.5 cpm data was available for comparison) at a temperature where oxidation is significant. No comparison of Astroloy out-of-phase TMF and low temperature isothermal data was possible due to a lack of baseline isothermal data.

The current IN100 isothermal crack growth model was used to predict TMF in-phase data. Good agreement was obtained at crack growth rates below 10^{-4} in./cycle. At this point, the model extrapolated beyond the fracture toughness of the material. This result was not unexpected, since the frequency is outside the bounds of the data used for the model.

Comparisons of all TMF crack growth rate data combined for Astroloy and IN100 are presented in Figures 16 and 17, respectively, with the corresponding SINH coefficients given in Tables 2 and 3. For both materials, the data can be distinguished according to the TMF cycle type (for example, in-phase or out-of-phase). In other words, negative stress ratio and minimum cycle temperature had negligible effect.

Integration of the crack growth model equation from the starting flaw size to the critical crack length results in the predicted life for a given set of test conditions. Comparison of the predicted versus actual (P/A) lives indicates the model can fit the TMF crack growth data quite well, and where no TMF data is available, a reasonable life prediction should be expected using isothermal data at the appropriate temperature.

All crack growth rate data generated in this task conformed to standards outlined in ASTM E-647 for constant load amplitude fatigue testing except the results for the out-of-phase TMF testing. In both materials, out-of-phase testing resulted in the development of large shear planes (Figure 18) which departed by more than ±5 degrees from the plane of symmetry. Initially, the shear was thought to result from the component of crack growth or damage that occurred during the compressive portion of the cycle. However, as testing progressed, similar shear planes developed in specimens with a stress ratio (R) of 0.1 (i.e., no compressive loading during the cycle).

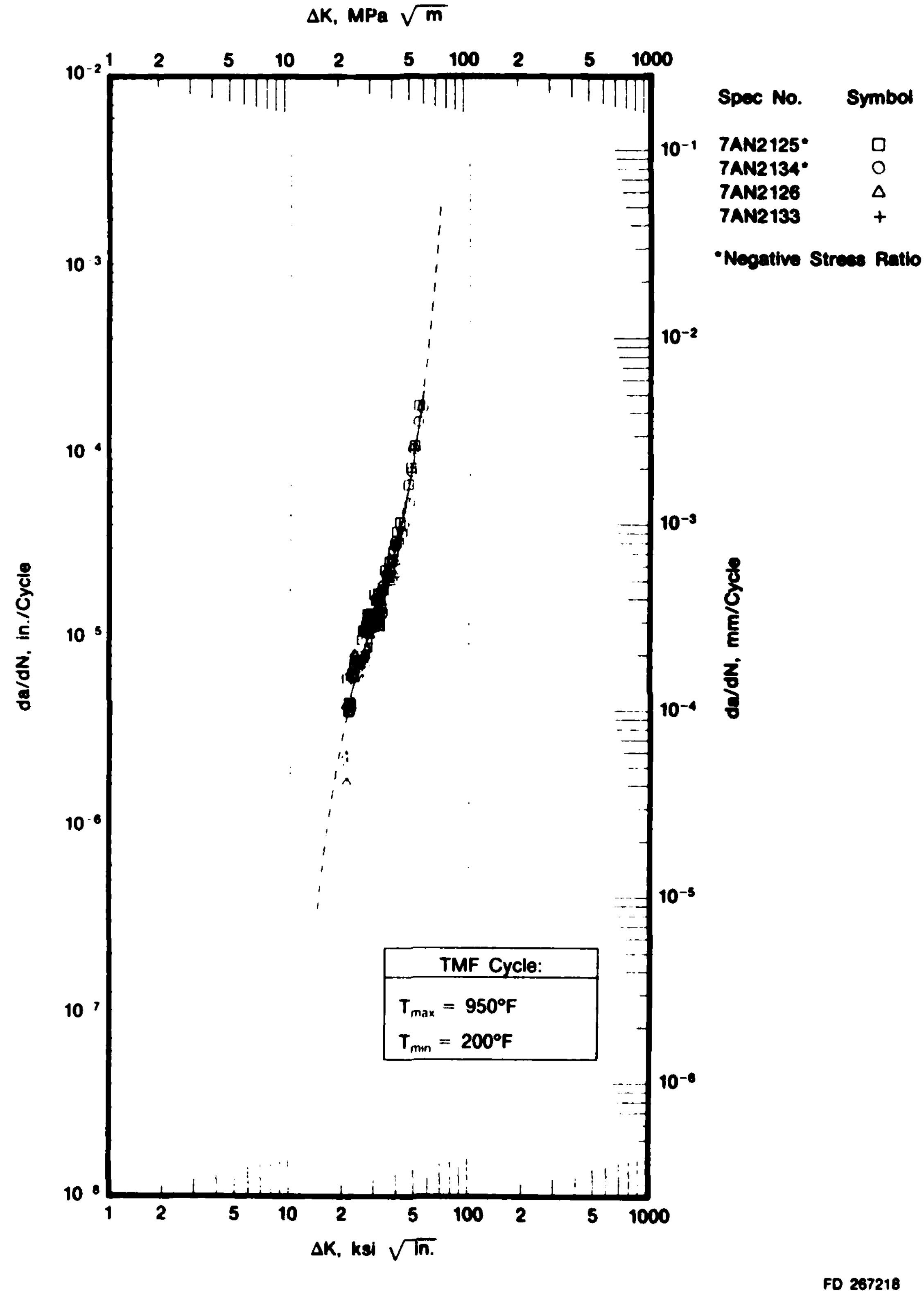

Figure 6. Negative Stress Ratio Has No Effect Compared With R=0.1 For Astroloy Subjected to Out-of-Phase TMF Cycle

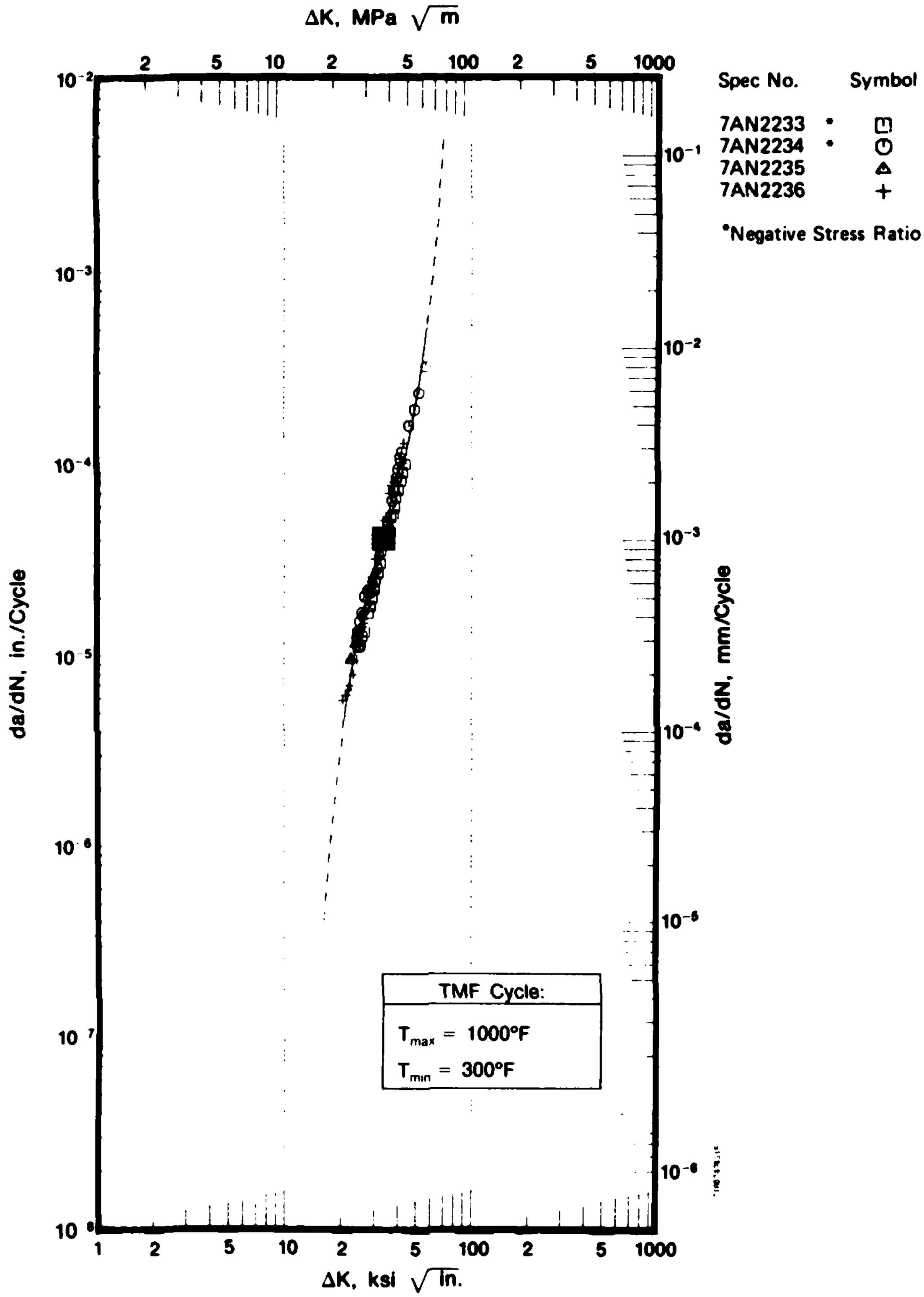

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Figure 7. Negative Stress Ratio Has No Effect Compared With R=0.1 For IN100 Subjected to Out-of-Phase TMF Cycle

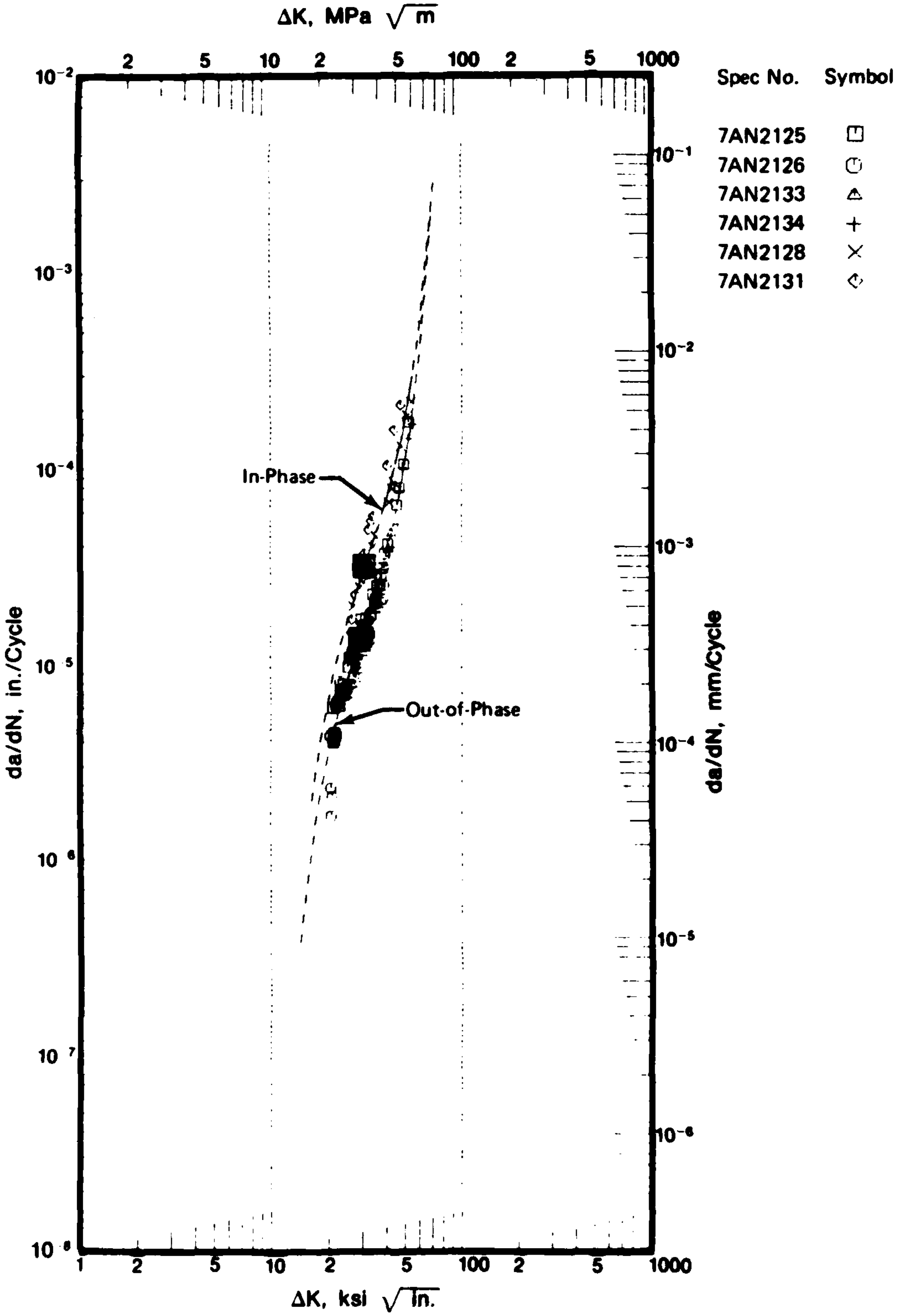

Figure 8. Effect of TMF Cycle Type on Astroloy for 200 to 950°F Temperature Range, 0.5 cpm

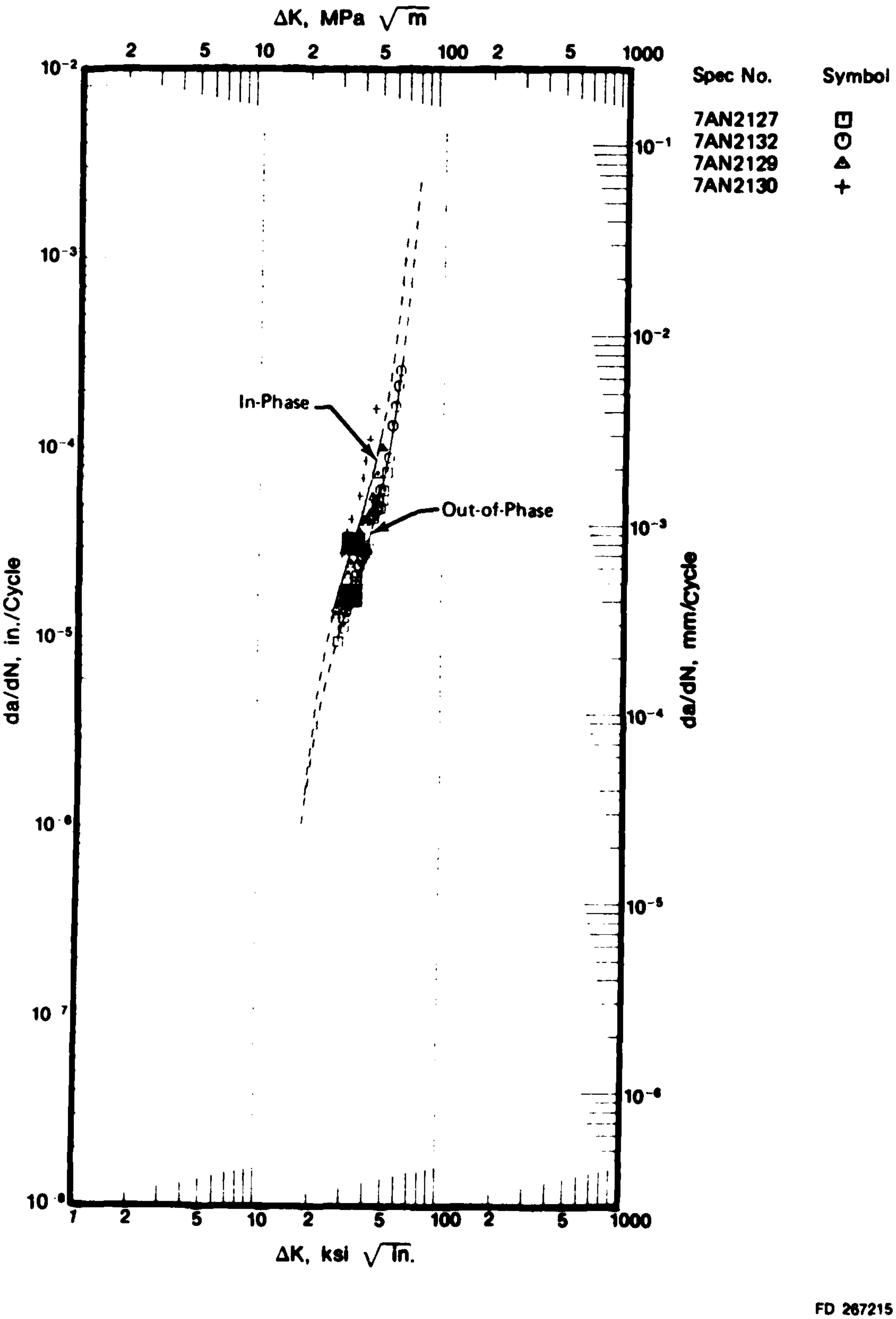

Figure 9. Effect of TMF Cycle Type on Astroloy for 500 to 950°F Temperature Range, 0.5 cpm

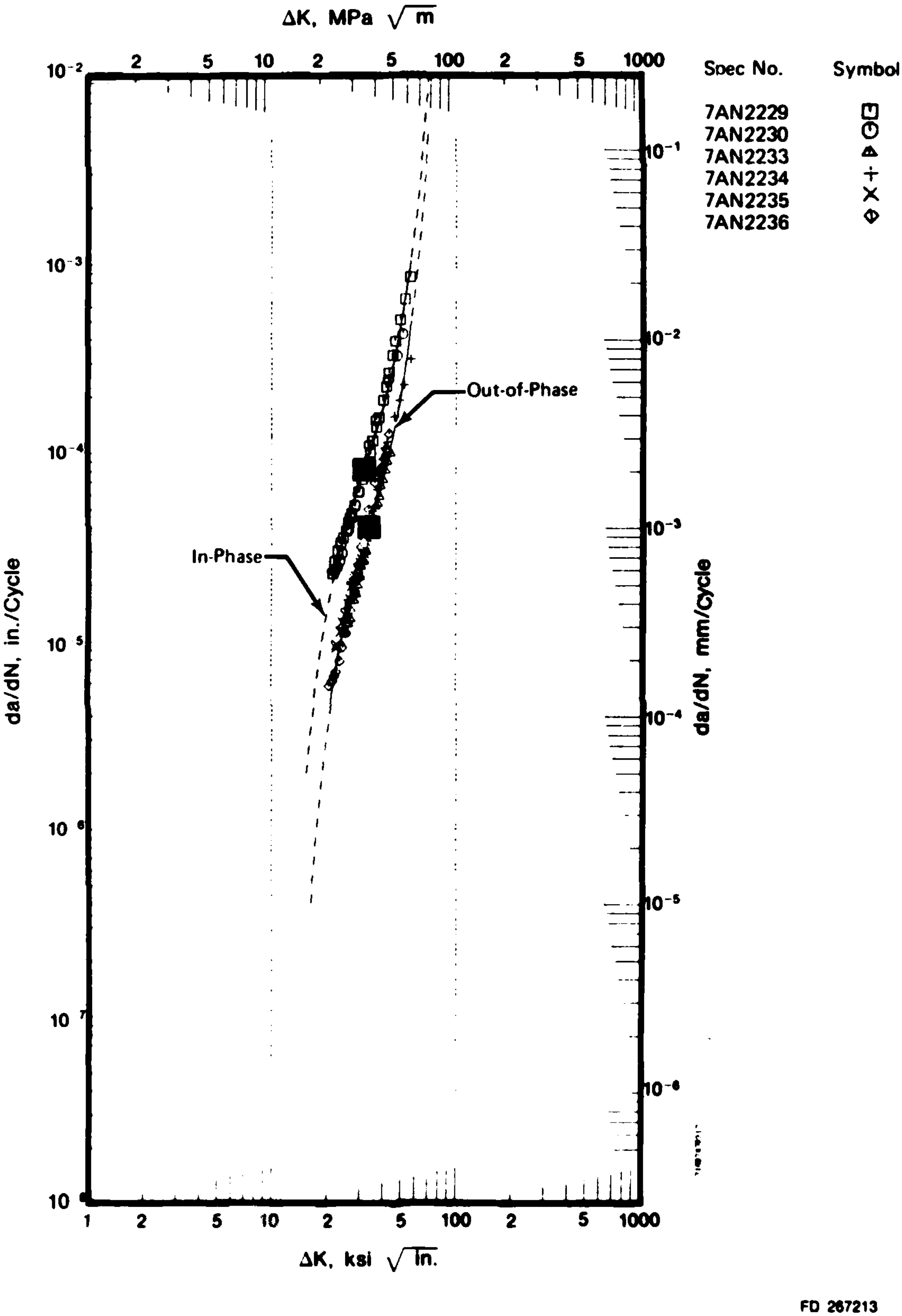

Figure 10. Effect of TMF Cycle Type on IN100 for 300 to 1000°F Temperature Range, 0.5 cpm

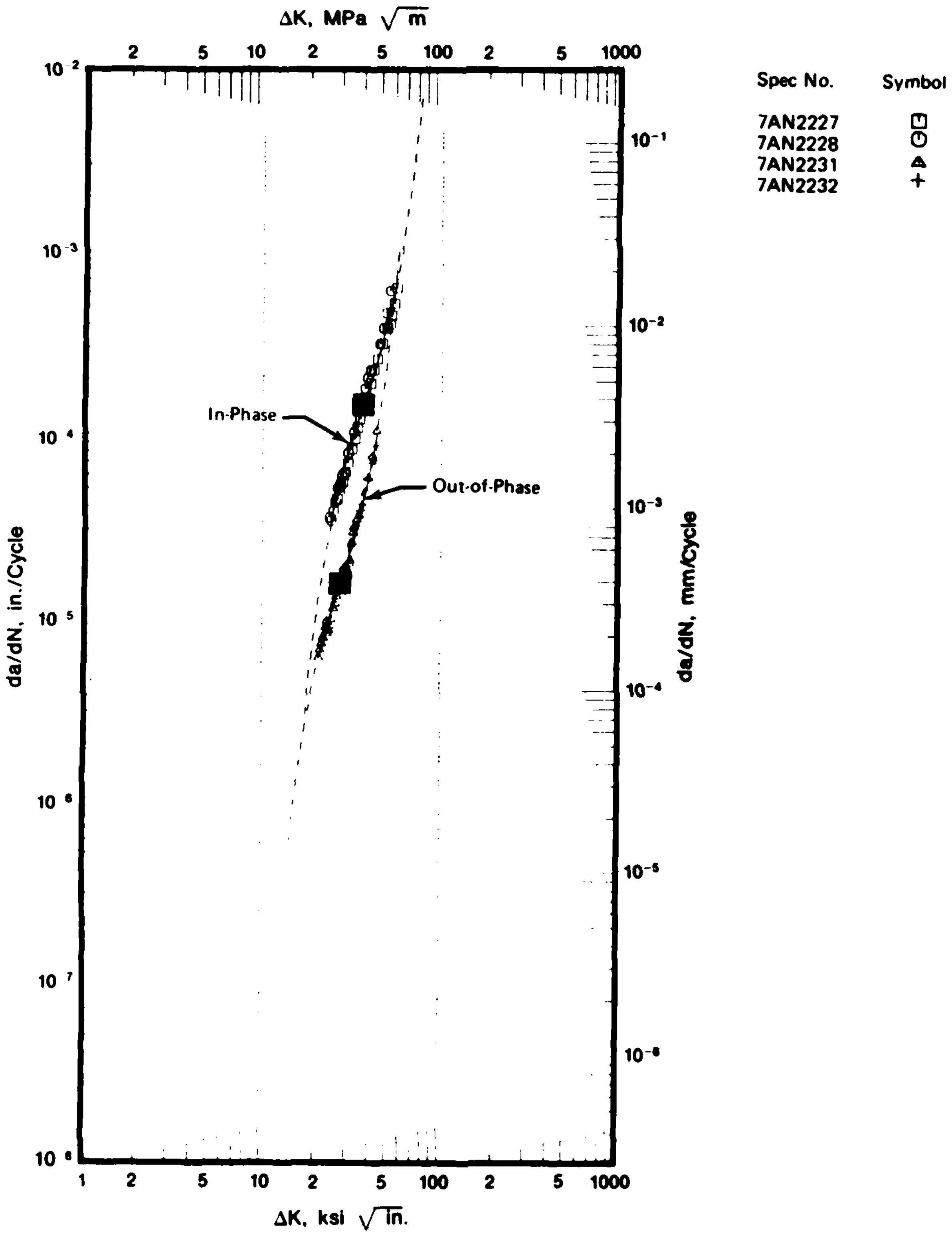

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Figure 11. Effect of TMF Cycle Type on IN100 for 500 to 1000°F Temperature Range, 0.5 cpm

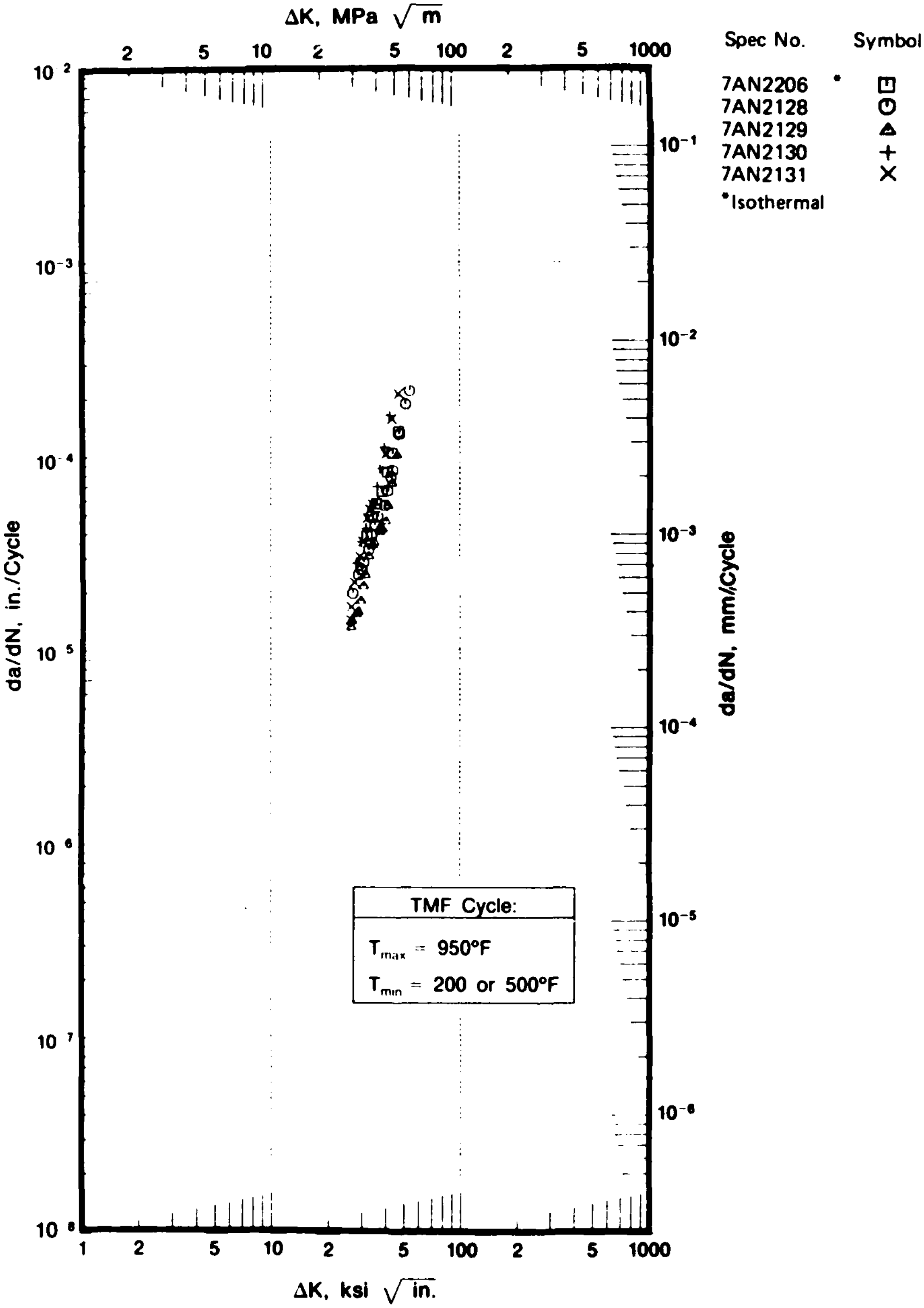

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Figure 12. Comparison of Astroloy TMF In-Phase (0.5 cpm) and Isothermal Crack Growth Rate Data at 950°F (0.5 cpm)

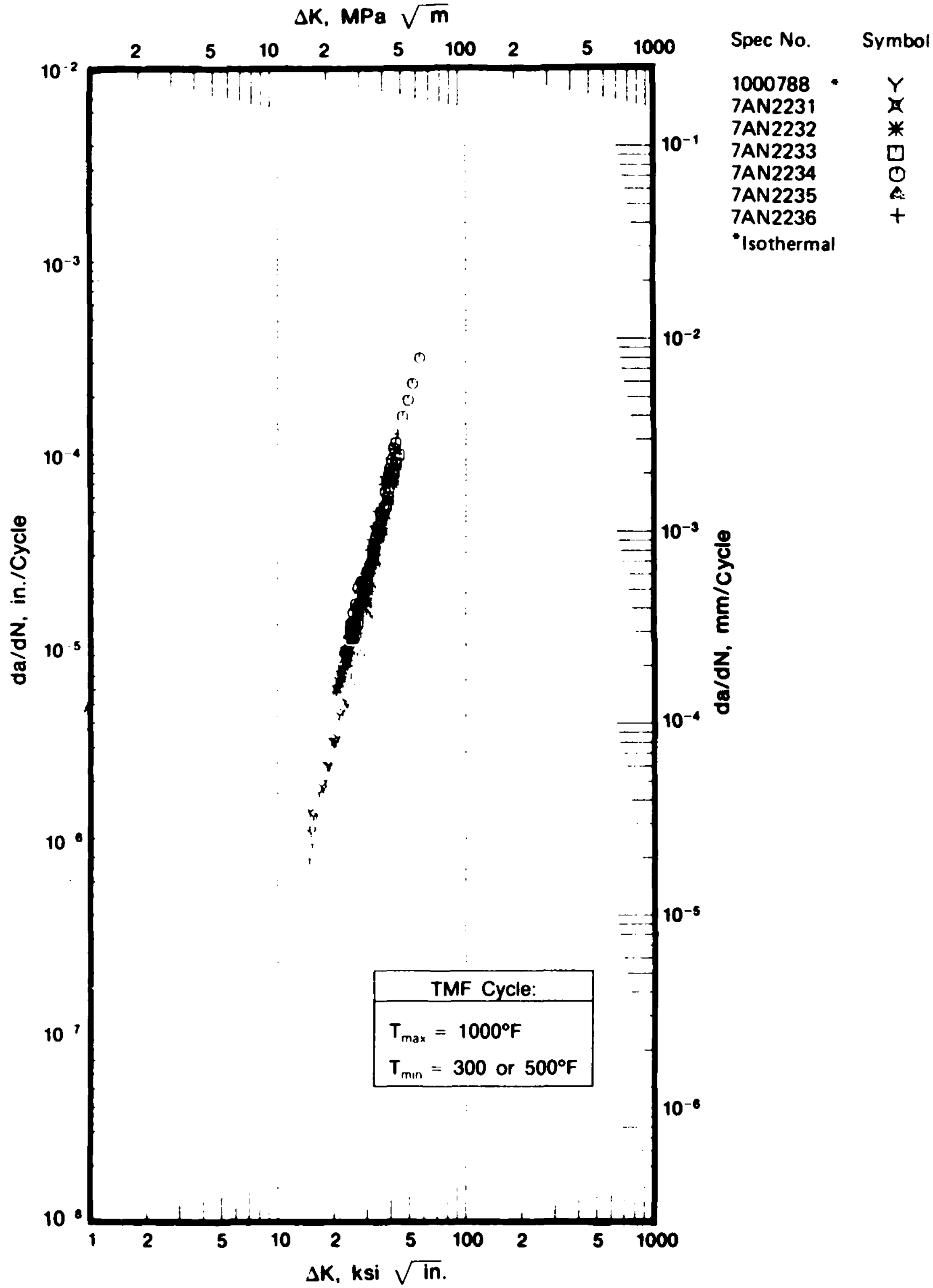

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Figure 13. Comparison of IN100 TMF Out-of-Phase (0.5 cpm) and Isothermal Crack Growth Rate Data at 300°F (10 cpm)

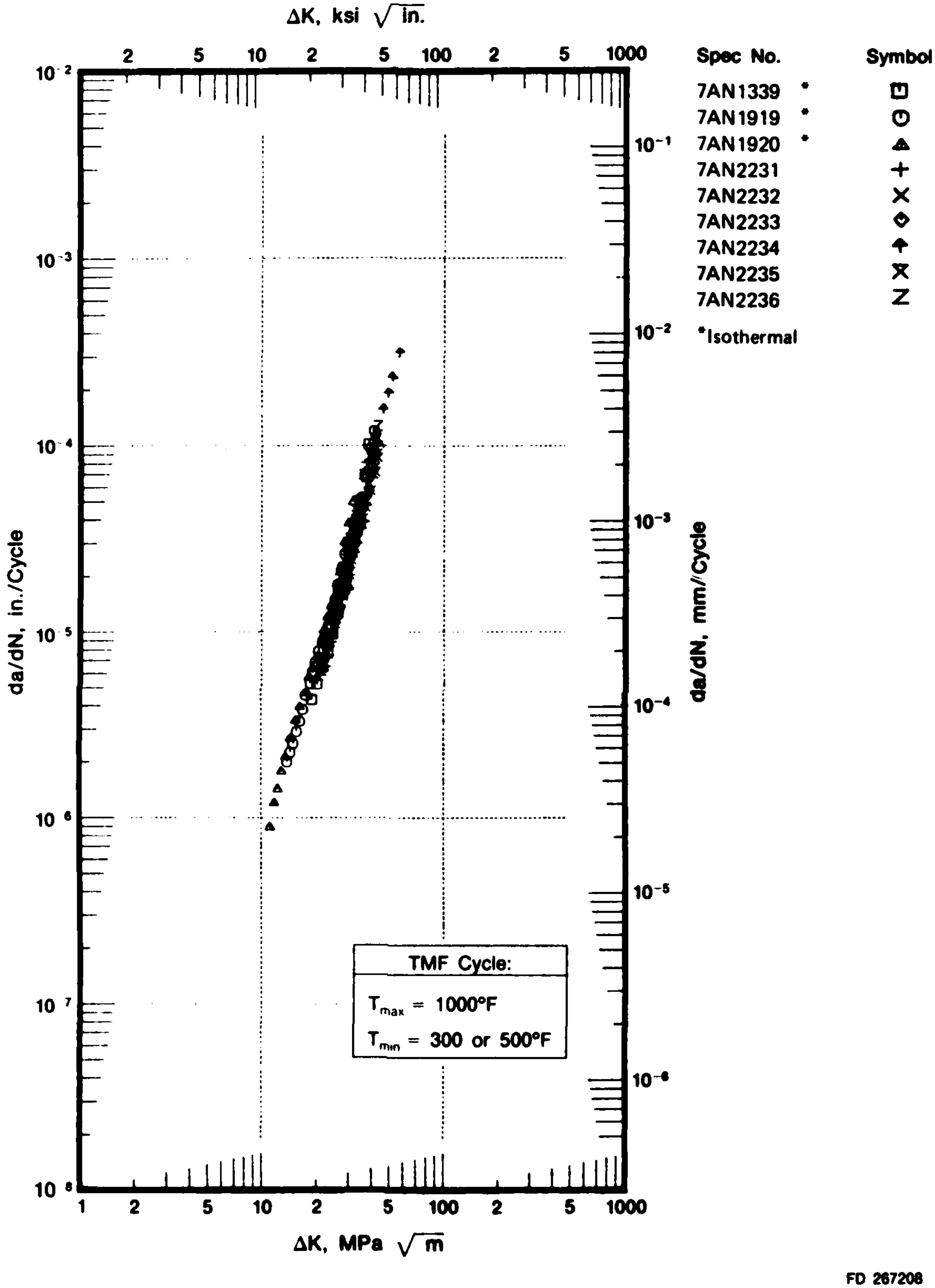

Figure 14. Comparison of IN100 TMF Out-of-Phase (0.5 cpm) and Isothermal Crack Growth Rate Data at 500°F (10 cpm)

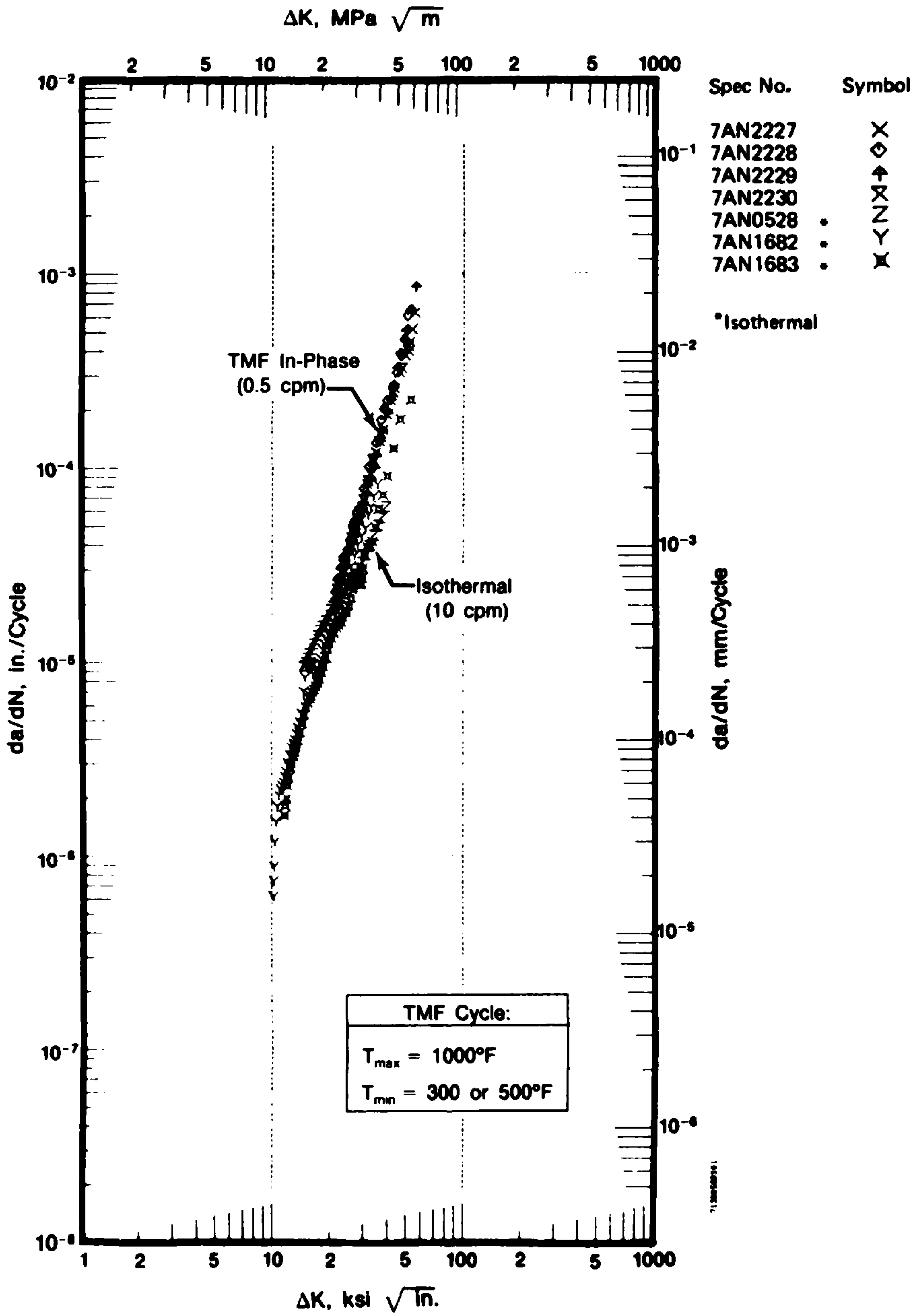

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Figure 15. Comparison of IN100 TMF In-Phase (0.5 cpm) With Isothermal Crack Growth Rate Data at 1000°F (10 cpm)

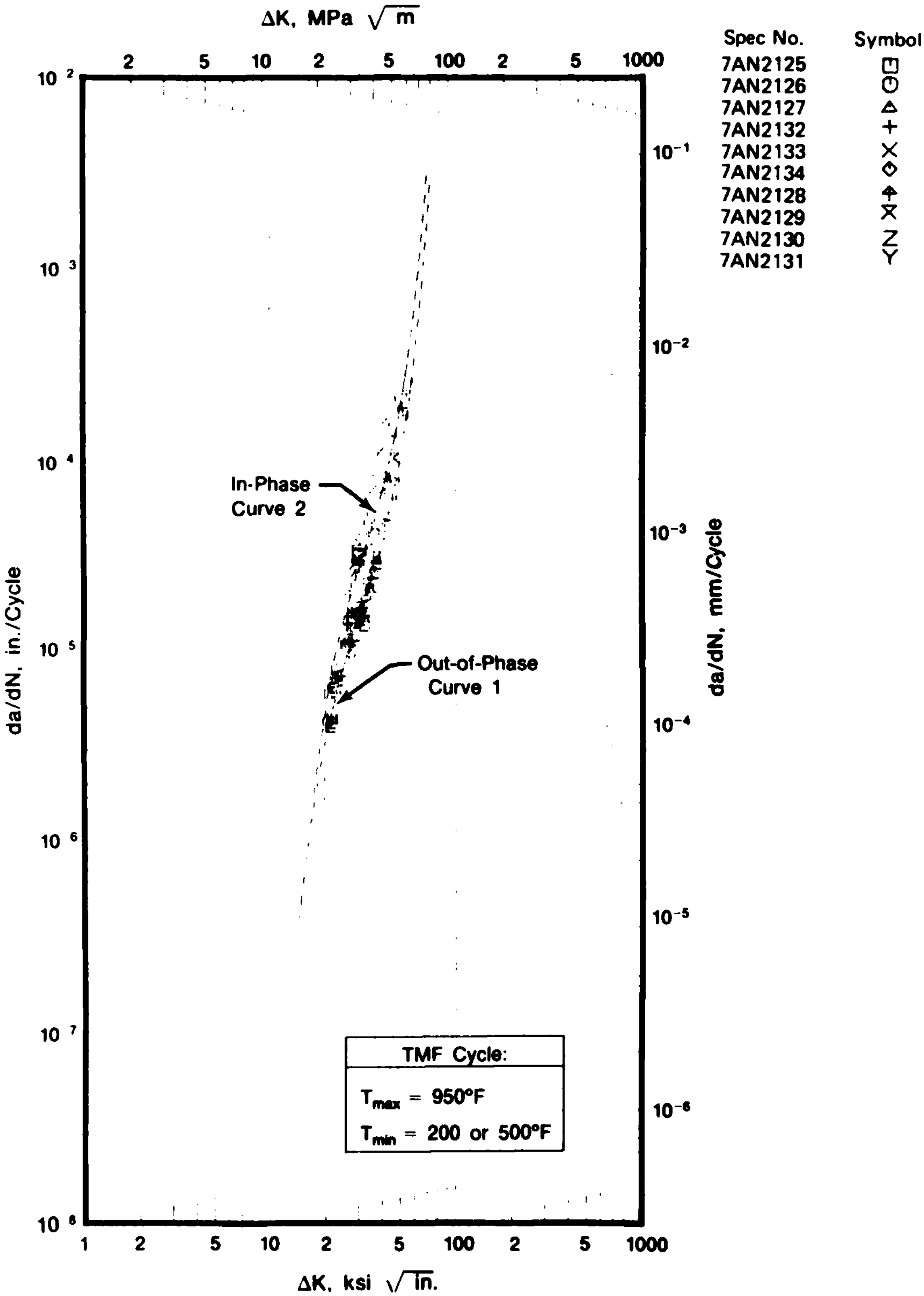

Figure 16. Effect of TMF Cycle Type on Astroloy at 0.5 cpm (All Data)

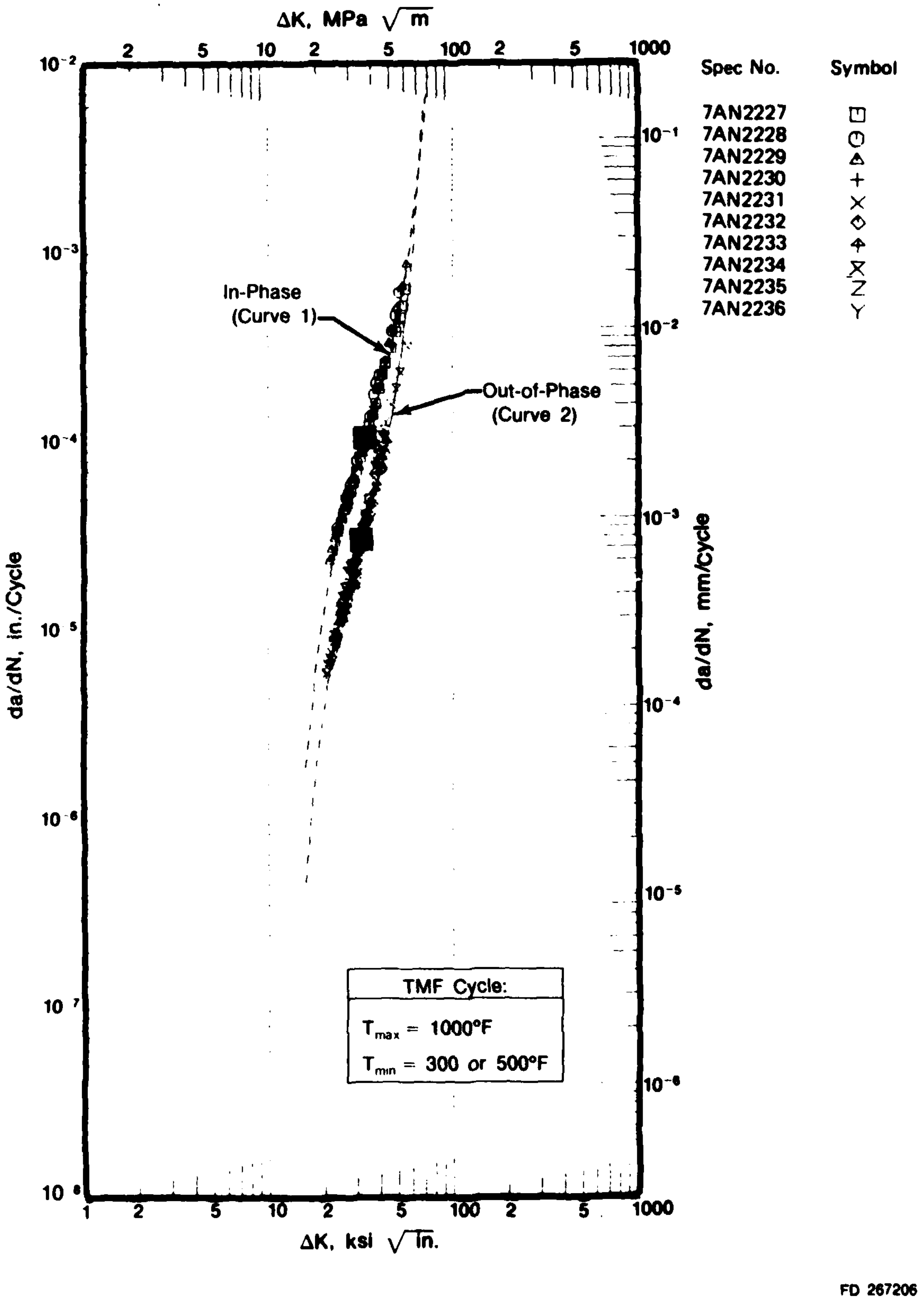

Figure 17. Effect of TMF Cycle Type on IN100 at 0.5 cpm (All Data)

TABLE 2. HYPERBOLIC SINE MODEL COEFFICIENTS FOR ASTROLOY TMF CRACK GROWTH RATE DATA

$$Y = C_1 \times \mathrm{SINH}\ (C_2 \times (X \times C_3)) + C_4$$

Where Y = log(da/dN) and X = log(Δ K)

Curve	C_1	C_2	C_3	C_4	*ΔK Range (min, max)*	*Number of Points*	*Correlation Factor (R^2)*	*Standard Error of Estimate*
1	0.5000	5.7970	−1.4770	−4.8560	(20.33, 58.35)	132	0.9707	0.0789
2	0.5000	6.1400	−1.5040	−4.5000	(26.47, 54.44)	51	0.8481	0.1280

Total RSQRD = 0.9577 Std Error Est = 0.0947

Curve	*Spec No.*	*Temp, °F*	*Freq.*	*Stress Ratio*	*Thickness, in.*	*Remarks*	*Predicted/ Actual*
1	7AN2125	200-950	0.5 cpm	−1.0	0.148	Out-of-Phase	1.067
1	7AN2126	200-950	0.5 cpm	1.0	0.150	Out-of-Phase	0.878
1	7AN2127	500-950	0.5 cpm	−1.0	0.149	Out-of-Phase	0.917
1	7AN2132	500-950	0.5 cpm	−1.0	0.149	Out-of-Phase	1.006
1	7AN2133	200-950	0.5 cpm	0.1	0.149	Out-of-Phase	0.767
1	7AN2134	200-950	0.5 cpm	−1.0	0.149	Out-of-Phase	0.817
2	7AN2128	200-950	0.5 cpm	−1.0	0.149	In-Phase	0.989
2	7AN2129	500-950	0.5 cpm	−1.0	0.150	In-Phase	0.813
2	7AN2130	500-950	0.5 cpm	−1.0	0.149	In-Phase	1.260
2	7AN2131	200-950	0.5 cpm	−1.0	0.149	In-Phase	1.162

TABLE 3. HYPERBOLIC SINE MODEL COEFFICIENTS FOR WROUGHT IN100 TMF CRACK GROWTH RATE DATA

$$Y = C_1 \times \mathrm{SINH}\ (C_2 \times (X \times C_3)) + C_4$$

Where Y = log(da/dN) and X = log(Δ K)

Curve	C_1	C_2	C_3	C_4	*ΔK Range (min, max)*	*Number of Points*	*Correlation Factor (R^2)*	*Standard Error of Estimate*
1	0.5000	6.0424	−1.5262	−3.9805	(21.39, 56.29)	78	0.9858	0.0513
2	0.5000	6.5882	−1.5034	−4.5224	(20.55, 56.85)	132	0.9620	0.0752

Total RSQRD = 0.9820 Std Error Est = 0.0674

Curve	*Spec No.*	*Temp, °F*	*Freq.*	*Stress Ratio*	*Thickness, in.*	*Remarks*	*Predicted/ Actual*
1	7AN2227	500-1000	0.5 cpm	−1.0	0.300	In-Phase	0.960
1	7AN2228	500-1000	0.5 cpm	−1.0	0.300	In-Phase	0.960
1	7AN2229	300-1000	0.5 cpm	−1.0	0.300	In-Phase	0.991
1	7AN2230	300-1000	0.5 cpm	−1.0	0.299	In-Phase	0.966
2	7AN2231	500-1000	0.5 cpm	−1.0	0.297	Out-of-Phase	0.941
2	7AN2232	500-1000	0.5 cpm	−1.0	0.299	Out-of-Phase	0.828
2	7AN2233	300-1000	0.5 cpm	−1.0	0.299	Out-of-Phase	0.916
2	7AN2234	300-1000	0.5 cpm	−1.0	0.298	Out-of-Phase	1.092
2	7AN2235	300-1000	0.5 cpm	1.0	0.298	Out-of-Phase	1.137
2	7AN2236	300-1000	0.5 cpm	1.0	0.300	Out-of-Phase	1.021

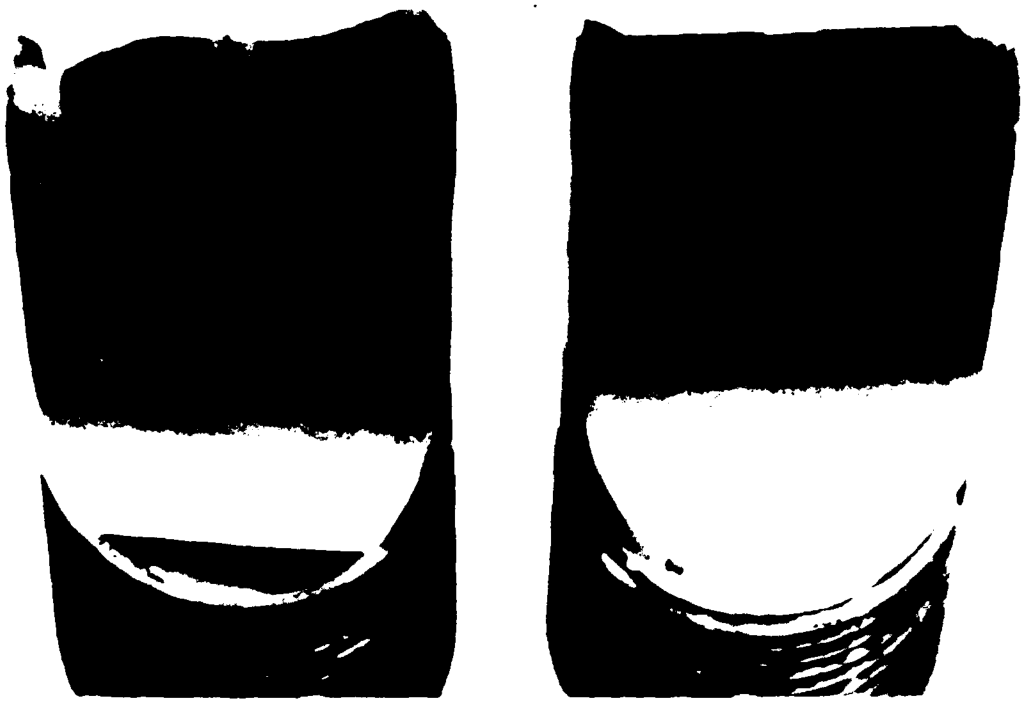

Figure 18. Comparison of Out-of-Phase and In-Phase Fracture Surface Morphology

Observations with regard to the out-of-phase fracture mechanism and results from previous tests provided the following:

1. No shear planes have been observed in the fracture of isothermal specimens tested previously with either negative or positive stress ratios at 149°C, 427°C, and 649°C (300°F, 800°F, and 1200°F).

2. No shear planes were observed in isothermal specimens tested in an inert environment. This condition is similar to the out-of-phase tests where minimum oxidation would occur as a result of the crack tip being opened only at the lower temperature.

Other hypotheses were tested with no satisfactory explanation for the appearance of the out-of-plane fractures.

SECTION V

CONCLUSIONS

The objective of this investigation was to assess the capability of the existing Hyperbolic Sine Model to predict accurately or conservatively the crack growth in gas turbine engine disks subject to thermal mechanical fatigue (TMF). The results of this task are summarized as follows:

1. Using the highest temperature of the in-phase TMF cycle, the existing isothermal model will accurately predict crack growth in gas turbine engine disks and spacers that are subject to thermal mechanical fatigue under conditions which reflect Retirement for Cause requirements.

2. Using the lowest temperature of the out-of-phase TMF cycle, the isothermal model again accurately predicts crack growth.

3. Crack growth rates under compressive loading at $R=-1$ did not differ from all tensile loading, $R=0.1$, for out-of-phase TMF cycling.

4. Out-of-phase TMF testing resulted in the development of large shear planes which had no noticeable influence on crack propagation rates measured normal to the loading axis, and for which no satisfactory explanation has been found.

It is concluded that no significant differences in crack growth rate prediction capability exist which would impact the successful implementation of the Retirement for Cause concept in the 1986 time frame for disks or spacers of Astroloy and IN100 under the conditions investigated.

These conclusions apply to the limited condition of primary concern to Retirement for Cause activity. As stated earlier, this effort was not intended to be an exhaustive investigation of thermal mechanical fracture mechanics. Therefore, the conclusions may not apply to other materials and conditions. Each investigator is encouraged to examine his own circumstances and assess these conclusions in that light.

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